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13. ABSTRACT (Maximum 200 words)

An innovative sensor suit is developed, which can be conveniently put on by an operator to detect his or her motion intention by non-invasively monitoring his or her muscle conditions such as the shape, the stiffness and the density. This sensor suit is made of soft and elastic fabrics embedded with arrays of MEMS sensors such as muscle stiffness sensor, ultrasonic sensors, accelerometers and optical fiver sensors, to measure different types of human muscle conditions. Compared with conventional sensors used in man-machine interfaces, the proposed sensor suit is soft, flexible, lightweight, easy to wear, accurate and reliable. More importantly, the sensor suit is auto-adaptive to an individual operator and does not impede motion against the operator. Furthermore, a failsafe mechanism using special hardware and active sensing software is incorporated in the sensor suit to ensure the safety and reliability. As a result, the sensor suit is ideal for use in man-machine systems, particularly the DARPA exoskeleton power suits. In this case, the sensor suit will be worn by the operator under the exoskeleton power suits. The sensor suit, with its distributed sensing capability, will provide accurate and reliable information about the operator's motion intention which is needed for controlling the power suit to accurately follow the operator's motion intention.

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(a) Manuscripts submitted, but not published

(b) Papers published in peer-reviewed journals

(1)Shunji Moromugi, Y. Koujina, Seigo Ariki, Akira Okamoto, Takayuki Tanaka, Maria Q. Feng and Ishimatsu Takakazu, (2004). "Muscle stiffness sensor to control assisting device for disabled", Journal of Artificial Life and Robotics, Vol.8, Num.1, pp.42-45.

(c) Papers published in non-peer-reviewed journals or in conference proceedings

(1) T. Tanaka, Y. Suzuki, Y. TsuTsui, M. Q. Feng and S. Moromugi, (2004). "Individual Difference and Measuring Point Error on Joint Torque Estimation Using EMG", Submitted for publication in *Transaction on JSME(Japan Society of Mechanical Engineering)*.

(2) Y. Tsutusi, T. Tanaka, Y. Suzuki, M. Q. Feng, S. Moromugi, (2004). "Torque Estimation Using Ultrasonic Muscle Activity Sensor", Submitted for publication in *Proceedings of ICAM200*.

(3) Y. Suzuki, T. Tanaka, Y. Tsutui, M. Q. Feng, (2004), "Wearable Sensor Suit (3rd Report, Auto-Calibration System for Joint Torque Estimation Using EMG)", Accepted for publication in *JSME ROBOMEC2004*.

(4) Yoshio Fukuda, Takayuki Tanaka, Maria Q. Feng, Takakazu Ishimatsu, (2005). "MEMS and Fiber Optics Sensor-Based Wearable Interface for Medical Applications", Submitted for publication in *Proceedings of IEEE SMC 2005*.

(5) Yoshio Fukuda, S.Moromugi, Maria Q. Feng, Takayuki Tanaka, Takakazu Ishimatsu, (2005). "MEMS and Fiber Optics Sensor-Based Wearable Interface for Medical Applications", Submitted for publication in *Proceedings of IEEE Sensors 2005*.

(6) Takashi Koyama, Takayuki Tanaka Shunichi Kaneko, (2005), "Integral Ultrasonic Muscle Activity sensor for Detecting Human Motion", Submitted for publication in *Proceedings of IEEE SMC 2005*.

(7) Takashi Koyama, Takayuki Tanaka Shunichi Kaneko, Syunji Moromugi, Maria Q. Feng (2005), "Integral Ultrasonic Muscle Activity sensor for Detecting Human Motion", Submitted for publication in *Proceedings of ISOT2005*

(8) Yousuke Suzuki, Takayuki Tanaka, Maria Q. Feng, (2005), "Auto-calibration system of EMG sensor suit", Submitted for publication in *Proceedings of ISOT2005*

(9) Seok-Hwan Kim, Shunji Moromugi and Takakazu Ishimatsu, (2004). "Development of advanced walking assist system employing stiffness sensor", Proceedings of 19th International Conference on Control, Automation and Systems, Bangkok, Thailand, pp.1638-1641.

(10) Shunji Moromugi, Hiroshi Owatari, Yoshio Fukuda, Seok-Hwan Kim, Motohiro Tanaka, Takakazu Ishimatsu, Takayuki Tanaka and Maria Q. Feng, (2005). "Wearable sensor network system for walking assistance", Proceedings of 20th International Conference on Control, Automation and Systems, Seoul, South Korea, pp.2138-2142.

b.(2) (a) 4, (b) 0, (c) 3, (d) 0

b.(3)

(a) 10, (b) 5, (c) 1, (d) 1, (e) 0, (f) 0, (g) 3, (h) 1, (i) 2, (j) 2, (k) 2, (l) 0, (m) 3, (n) 2

b.(3)

1.Muscle stiffness sensor
2.Muscle density sensor using ultrasonic sound
3.MEMS Accelerometer for position measurement
4.Optical fiber for joint angle measurement
5.3D Measurement system using image processing
6.Sensor network

b.(4)

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1. Introduction

An innovative sensor suit is developed, which can be conveniently put on by an operator to detect his or her motion intention by non-invasively monitoring his or her muscle conditions such as the shape, the stiffness and the density. This sensor suit is made of soft and elastic fabrics embedded with arrays of MEMS sensors such as muscle stiffness sensor, ultrasonic sensors, accelerometers and optical fiver sensors, to measure different kinds of human muscle conditions. In this project period, we successfully developed the sensor suit, which is based on EMG sensors. Moreover, the various technologies we developed in this project such as a MEMS accelerometer, a fiber optic sensor, a muscle stiffness sensor and muscle density sensor are evaluated those applicability of the measurement of human body condition through various experiment. Now, these sensors we developed are introduced various application field, and achieve a successful outcome. The details and the experimental results about our sensor suit and sensors we developed in this project are shown below.

2. Muscle Stiffness Sensor and Its Application

2.1 Muscle stiffness sensor

An innovative sensor is developed as a man-machine interface to detect operator's intention for controlling the assisting device. The sensor detects stiffness information form a target muscle. The activation level of the muscle can be estimated from the obtained stiffness data of the muscle because the muscles always get stiff when they act. The muscle activation obtained from the sensor is used to derive a command signal thus the operator can maneuver the mechanical glove with desired force at proper timing. It would be the best if the muscle of the operator's forefinger were still active and available as command muscle. However, muscles of the operator's fingers are completely inactive. Thus the muscle, Flexor Carpi Ulnaris, that is originally for wrist flexing is used as the command muscle. Figure 2.1 shows the muscle stiffness sensor. This sensor has two components, a flat disk (32mm in diameter and 12mm in thickness) and a button (6mm in diameter and 4mm in height) in the center of the disk. The whole weight of the sensor without the cable is 34g. This sensor is attached on the target muscle and tightened by a belt. Two small pressure sensors are used to measure the force loaded on the button and the force on the entire sensor.

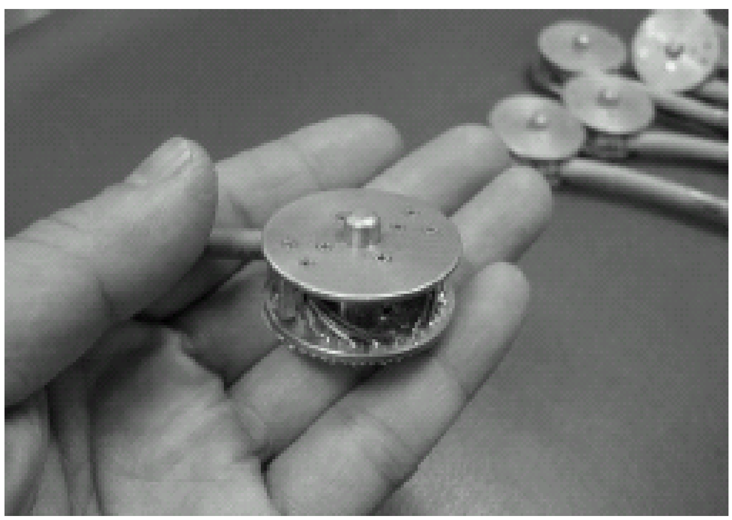


Fig.2.1 Muscle stiffness sensor

2.2 Device for Assisting Grasping Function

To evaluate the applicability of our muscle stiffness sensor for sensor suit, A wearable device is developed to recover the patient's fingering function. This device is put on operator's hand and helps his fingering function. Operator's forefinger is guided toward his fixed thumb by the mechanical glove. The forefinger is actuated by an air cylinder based on an operator's command signal. An unique sensor is developed in this study and used as a man-machine interface to control the device. The sensor is attached to one of his sound muscles called Flexor Carpi Ulnaris for wrist flexion. He can comfortably control its activation level. The muscle is called as command muscle since he can operate the assisting device through the activation of the muscle. The sensor detects the muscle activation level non-invasively. Based on the muscle activation level, the grasping timing and force are determined. It is confirmed through experiments that the patient can pick up small daily necessaries such as a pen and a cup with his finger by using this assisting device.

2.3 System configuration

Figure 2.2 shows the configuration of the assisting device. This device is composed of a mechanical glove, a muscle stiffness sensor, an air control unit and a computer. The operator sends command signals to the controller through the muscle stiffness sensor

attached on his arm. The controller regulates air pressure inside the air cylinder of mechanical glove based on the command signals so that the fingering operation is achieved based operator's intention.

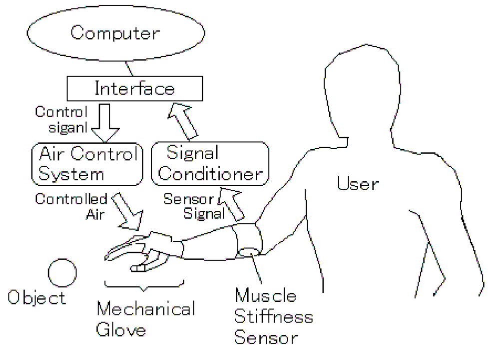


Fig.2.2 System configuration

2.4 Mechanical glove

Figure 2.3 and Figure 2.4 show the developed mechanical glove and its structural sketch respectively. The mechanical glove is composed of a finger frame to flex a forefinger and a base to be attached on the hand and an air cylinder mounted on the base. The finger frame consists of three links, link 1, link 2 and link 3 as shown in the Fig.3. Each link is connected by small sub-links each other. All joints of the finger fame are driven simultaneously with the actuation of an air cylinder. The total weight of the mechanical glove is 110[g].

Fig. 2.3 Mechanical glove

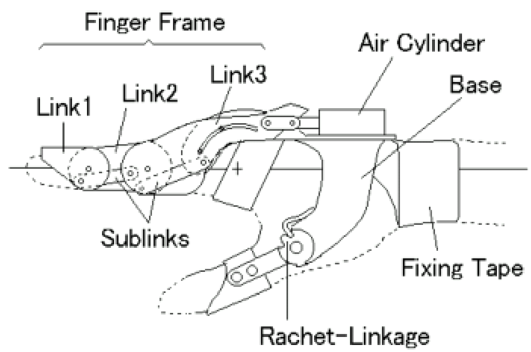


Fig.2.4 Structure of mechanical glove

2.5 Control system

Figure 2.5 shows the configuration of the control system. A personal computer (PC) sends and receives signals through a Field Programmable Gate Array (FPGA) to control the air cylinder of the mechanical glove. Muscle stiffness information and air pressure inside the air cylinder are fed to the PC through a signal conditioning circuit. FPGA generates Pulse Width Modulation (PWM) signals to control solenoid valves. A pair of solenoid valves is used to control air pressure of each chamber of the air cylinder. One is for pressuring and the other is for exhausting. Air pressure inside the both chambers is always monitored with air pressure sensors. A duty ratio of PWM signal is decided to control each valve so that the pressure inside the air cylinder always follows the reference pressure. The reference pressure is given by the equation (1).

$$\begin{aligned} P_{RE} &= P_B \\ P_{RF} &= P_B - P_{0F} + K \times S \end{aligned} \qquad (1)$$

where,

P_{RE} : Reference pressure of chamber for extending
P_{RF} : Reference pressure of chamber for flexing
P_B : Base pressure
P_{0F} : Offset pressure for extending finger under no command signals
K : Control gain
S : Muscle stiffness parameter

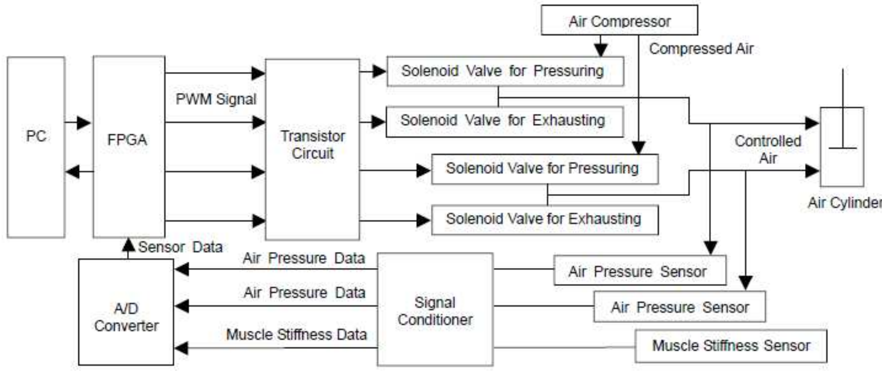
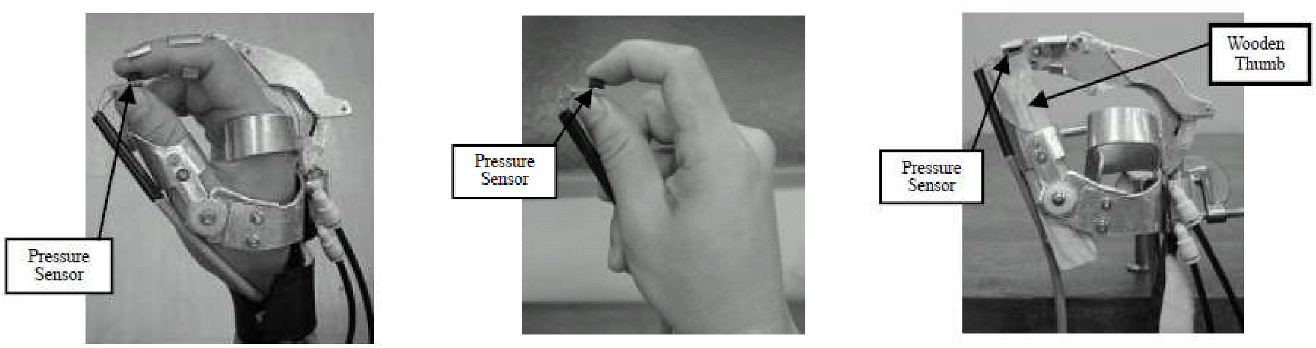


Fig.2.5 Control system

2.6 Experiment

The accuracy of the pinching force is compared between the case of the patient with the assisting device and the case of non-disabled examinees with their own ability. Before the maneuverability evaluation, the basic property of the assisting device is examined. The pinching force of the mechanical glove is recorded under stepwise input signal. Eq.(1) shows the control algorithm of the assisting device. The mechanical glove is kept opened under the condition that the commandmuscle is relaxed. As the command muscle is activated, the pressure inside the cylinder chamber for flexing finger is increased. Fig.6 shows the pinching force measured under a stepwise input signal. The maximum pinching force is about 2.3 [N]. This limitation of pinching power comes from the capability of air compressor. There are also limitations of increasing/decreasing ratio of pinching force. The maximum increasing and decreasing ratio of the pinching force is about 0.5[N/s] and 0.75[N/s] respectively. This limitation comes from the capability of solenoid valves. Based on these limitations, the amplitude and the frequency of the reference pinching force are decided for the maneuverability evaluation. The patient introduced at the beginning of this paper and 3 non-disabled examinees take part in this experiment. All examinees are male. Examinee A, examinee B and examinee C are 30, 32 and 22 year old respectively. In the experiment, examinees pinch a pressure sensor with their forefinger and thumb. The pinching force measured by the pressure sensor is displayed on the computer screen. A reference pinching force that is sinusoidal curve with amplitude 0.7[N] and randomly variable frequency, 0.18-0.25[Hz] is also displayed on the screen. The examinee is required to control the pinching force to be equal to the reference force for 15 second during the experiment. The Root Mean Square Error (RMSE) between the measured pinching force and the reference pinching force is recorded as a score to evaluate the maneuverability. The Experiment is conducted for three cases as shown in Figure 2.6.



Case 1 Fingering operation of patient with assisting device

Case 2 Fingering operation of non-disabled examinee

Case 3 Fingering operation of non-disabled examinee with assisting device

Fig.2.6 Experimental setup

In the Case3, the mechanical glove is tested on a bench because it is found out that finger moves unconsciously when the non-disabled examinee try to operate the mechanical glove. A wooden thumb is attached to the mechanical glove to set a pressure sensor on it instead of the operator's finger so that pinching force can be measured without unintentional affect of examinee's muscular function.

2.7 Experimental result

Figure 2.7 shows patient's pinching force measured in the experiment of Case1. It is clear that the patient succeeded to control the assisting device to match the pinching force to the reference force displayed on the computer screen. Figure 2.8 and Figure 2.9 show examinee A's pinching force measured in the experiment of Case2 (without assisting device) and Case3 (with assisting device) respectively. The data of Case2 are rather smoother than that of Case3 however no remarkable difference can be recognized in the

amount of error under finger force control between these two cases. The patient's scores obtained through five measurements and the average value are shown in Figure 2.10. Learning effect can be recognized at the first part of the measurements. Figure 2.11 shows the examinee A's score of five measurements in both Case2 & Case3. It can be seen that the level and the tendency of the error is quit similar between these three data in Figure 2.10 and Figure 2.11. Similarly, the same measurement is repeated for the examinee B and examinee C. The average score of all the examinees are shown in Figure 2.12. By the help of assisting device the patient's score becomes similar to that of non-disabled examinees. The assisting device successfully recovers patient's fingering function and achieves the similar level of dexterity on controlling the finger force.

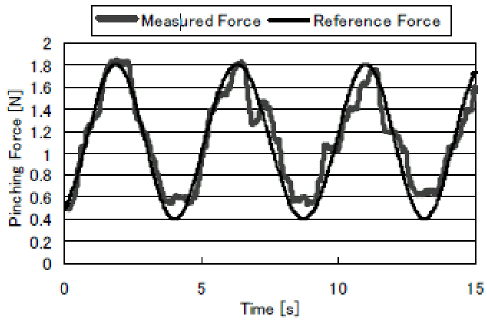


Fig.2.7 Experimental data of patient (case 1)

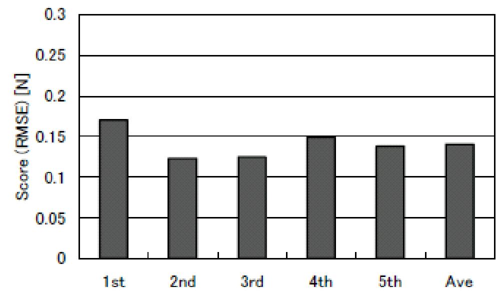


Fig.2.10 Score (case 1)

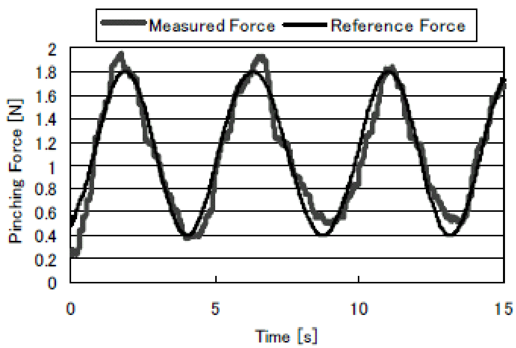


Fig.2.8 Experimental data of examinee A (case 2)

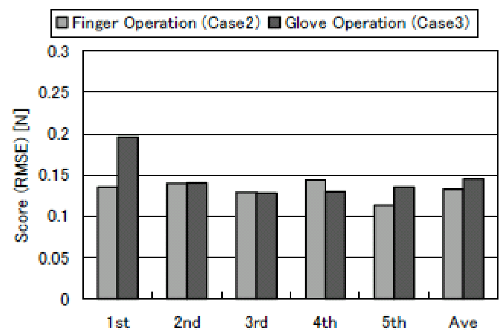


Fig.2.11 Score of examinee A (case 2 & case 3)

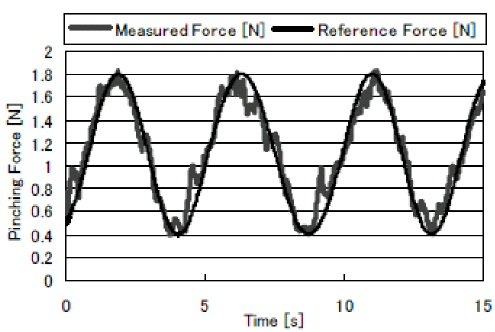


Fig.2.9 Experimental data of examinee A (case 3)

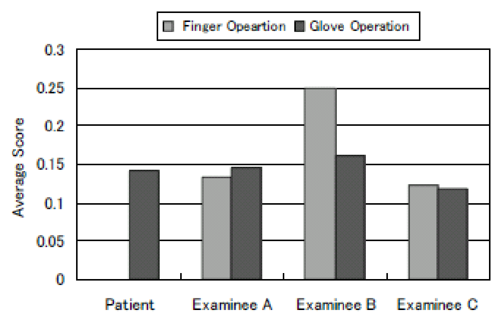


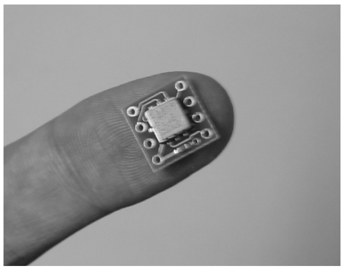
Fig.2.12 Five times average score of all examinee (case 1, 2 and 3)

2.8 Summary

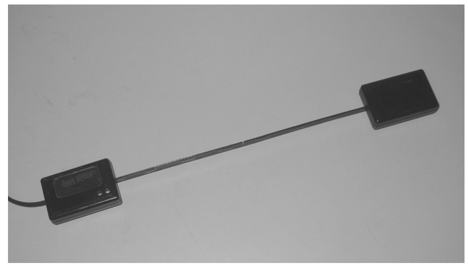
A wearable device that assists fingering function is developed for a disabled patient and its maneuverability is experimentally evaluated. Dexterity on controlling fingering force is evaluated in the following three cases. In the first case a patient who completely disabled fingering functions operated his finger by the help of the assisting device. In the second case non-disabled examinees operated their finger by their own ability. In the third case non-disabled examinees operated their finger indirectly by using the assisting device. No remarkable difference can be recognized in dexterity of fingering operation between these three cases. It can be said that the assisting device developed in this study recovers fingering function of disabled with the equivalent level to that of ordinary people on finger force control. It is demonstrated that the assisting device has enough maneuverability for its control through the experiments.

3. MEMS Accelerometer and Fiber Optic Sensor

To measure the position and motion of a human's body, we developed sensing systems using MEMS accelerometers and optical fiber sensors shown in Figure 3.1. The accelerometer can detect the angular displacement by using the gravity acceleration, and the optical fiber sensor can detect the bending angle of a joint. Figure 3.2 (a) and (b) respectively show the angles measured by the accelerometer and the optical fiber sensors compared with the actual angles. Each measurement is repeated several times. Excellent repeatability and measurement accuracy are observed. Compared with the accelerometers, the optical fiber sensors are more accurate and thus are recommended for measuring the major joints of a human body. On the other hand, the accelerometer is small in size and thus easy to monitor the entire human body.

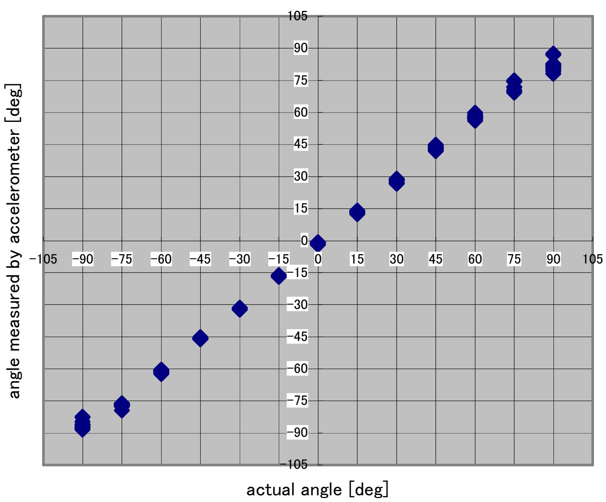


(a) Accelerometer

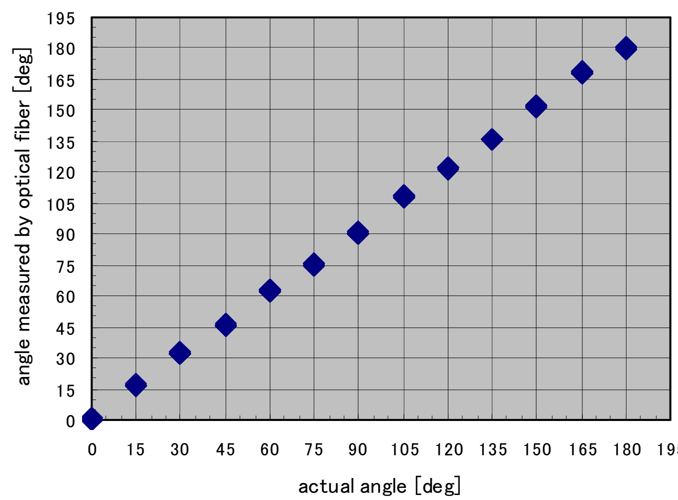


(b) Optical fiber sensor

Fig.3.1 Sensors for measuring body position



(a) Angle measured by the accelerometer



(a) Angle by the optical fiber sensor

Fig.3.2 Experimental result of each sensor

4. EMG Sensor

4.1 Muscle stiffness estimation using EMG sensor

An EMG is a microscopic electrical charge, which is generated when a muscle contracts. By detecting this electrical charge, the muscle activity can be estimated. An EMG sensor is embedded in our sensor suit, as shown Figure 4.1, to detect the electrical charge. Figure 4.2 shows the correlation between the muscle stiffness obtained from a muscle stiffness sensor (developed earlier in this project) and the EMG obtained from EMG sensor.

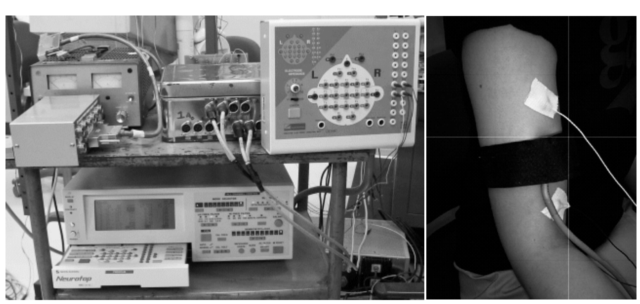


Fig.4.1 EMG sensor

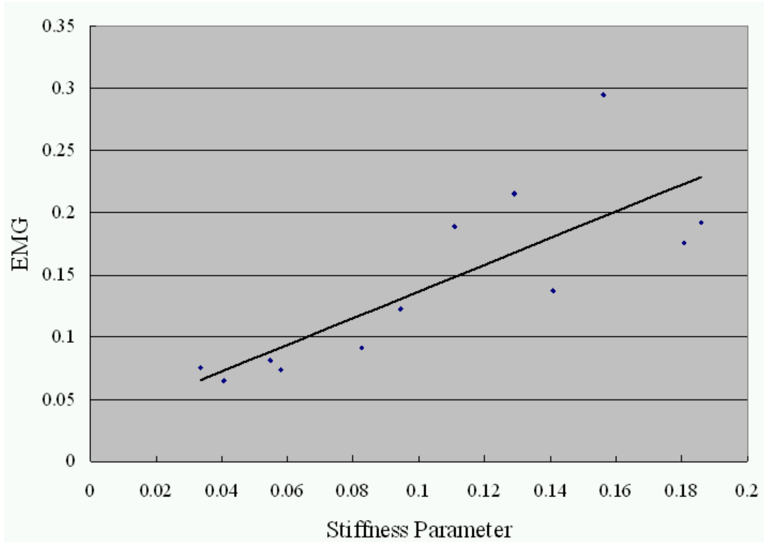


Fig.4.2 Correlation between EMG and muscle stiffness

4.2 Estimation of dynamic torque of elbow joint using reflective ultrasonic muscle activity sensor

We developed an auto-adaptive calibration system using EMG sensors and experimentally confirmed its effectiveness. During this year, we developed an auto-adaptive system based on neural networks using muscle activity sensors. We developed a reflective ultrasonic sensor as the muscle activity sensor. By using this sensor, both the reflected ultrasound and the transmitted ultrasound can be detected at same time. As a result, the accuracy is improved dramatically and it becomes possible to measure the activities of the muscles behind bones.

Figure 4.3 shows the developed sensor cuff embedded with 7 ultrasonic sensors. This sensor cuff can detect the reflected ultrasound sound and transmitted ultrasound sound at the same time. Figure 4.4 shows the reflected ultrasound (R1 and R2) and transmitted ultrasound (R3 and R4) when the ultrasound is transmitted from the transmitter T1. Figure 4.5 shows the actual ultrasound waveform obtained from the receivers R1, R2, R3 and R4.

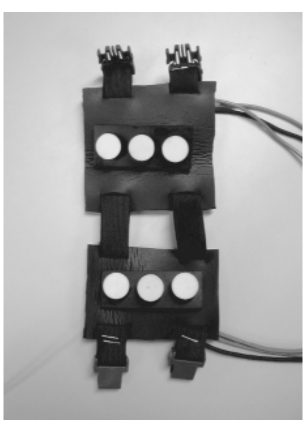


Fig.4.8 Reflective ultrasonic sensors embedded in small cuff

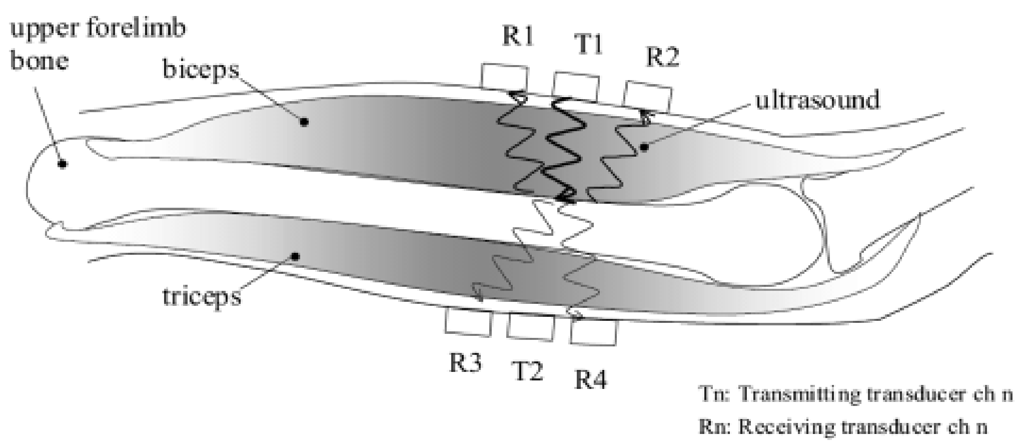


Fig.4.4 Reflected ultrasonic sound and transmitted ultrasonic sound

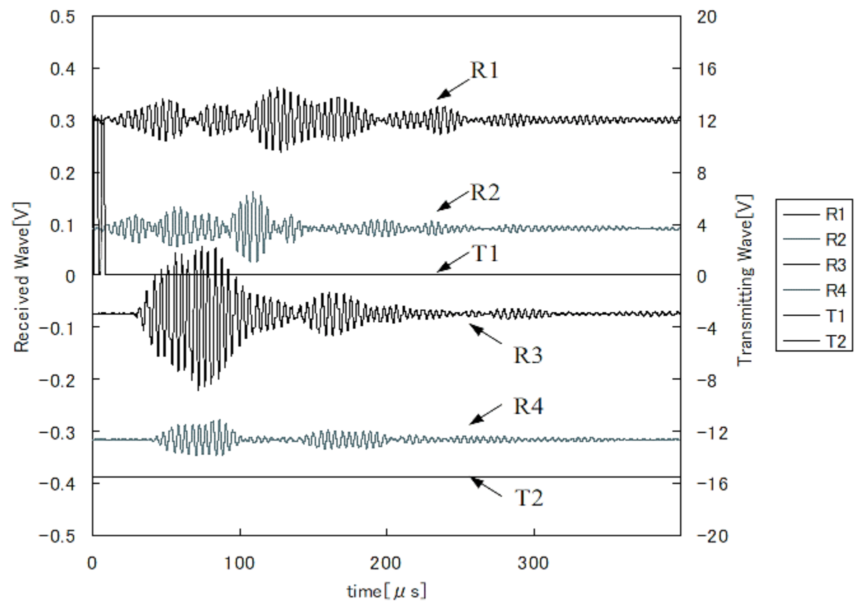


Fig.4.5 Waveform of transmitting (T1) and receiving (R1-R4) ultrasound.
(Waves are added offset for plotting)

4.3 Experiment and result

Figure 4.6 shows the experimental setup for estimating the torque of human arms based on the sensor data from the sensor cuff. To measure the actual torque for the reference, we used the torque measurement equipment as shown in Figure 4.6. By an examinee grabs a handle attached on its tip, the bending movement of his/her arm and the joint movement of the torque measurement equipment are synchronized. At this time, the actual torque of elbow joint is obtained by a torque sensor attached on the joint of this equipment. The examinee wears the sensor cuff on his/her arm to estimate the joint torque, and then attaches torque measurement equipment to measure actual torque as the reference values. For the learning purpose, the examinee follows the pre-specified elbow bending motion instruction displayed on a monitor to moves his/her arm. From measured sensor data, the arm torques of the examinee are estimated dynamically using a pre-designed neural networks. Figures 4.7 and 4.8 show the experimental result. In this figure, τ shows the actual torque measured by the torque measurement equipment, τM shows the torque estimated by multiple regression analysis and τN shows the torque estimated by the neural network. We performed 7 experiments (2nd to 8th) after 1 learning motion (1st) as shown in Figure 4.7. As shown in this figure, the estimated torque agree with the measured torque with high accuracy.

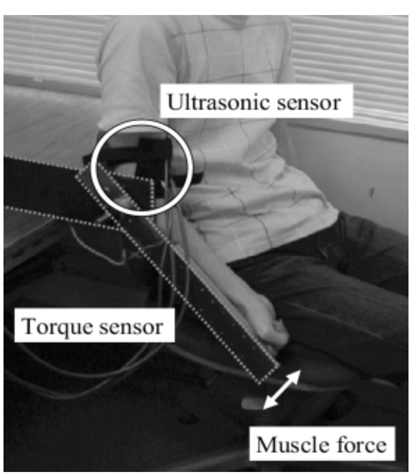


Fig.4.6 Experimental setup

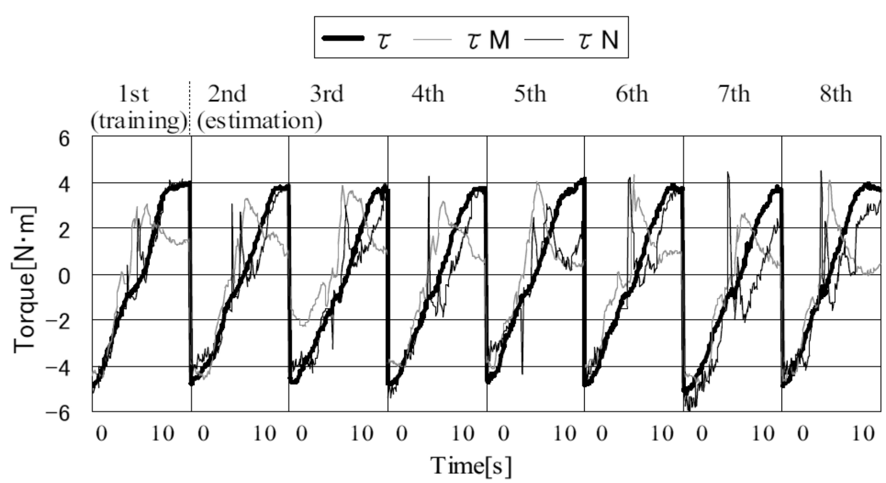


Fig.4.7 Estimated and measured torque
(τM:Estimation by multiple regression analysis)
(τN:Estimation by neural network)

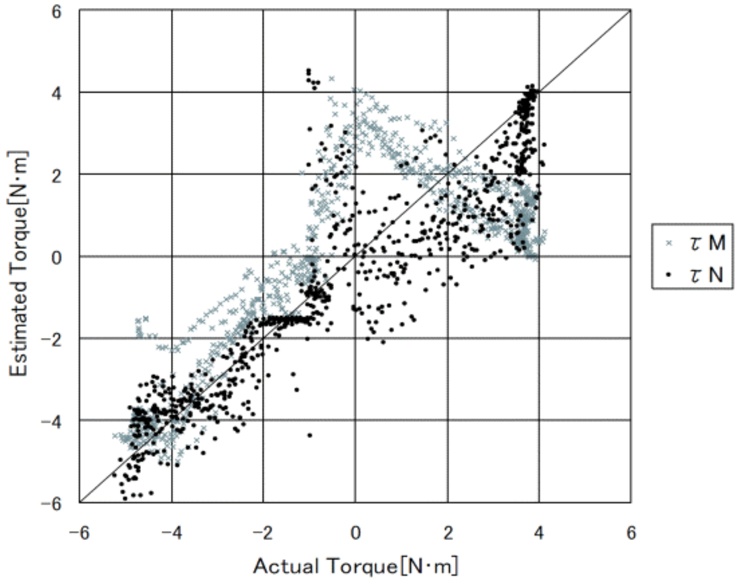


Fig.4.8 Comparison of estimated and measured torques
(τM:Estimation by multiple regression analysis, τN:Estimation by neural network)

5. 3D Measurement and Imaging Processing System for Detection Muscle Position and Boundary

A 3D measurement and imaging processing system for detection human muscle shape has been developed. A human muscle boundary analysis is one of the key issues for our sensor suit. These kinds of information measured by this 3D measurement system is used for estimation of optimal sensor position ant it makes our sensor suit more accurate and reliable. Especially, the analysis of shifting of human muscle boundary responding to operator's body movement is important information to estimate optimal sensor positions. By using our system, the human muscle boundary lines drawn by an expert of surface anatomy to examinee's body and examinee's body shape can be obtained as a 3D model data accurately and quickly. Furthermore a database of muscle boundary lines can be created at short times.

5.1 System configuration

A developed system consists of a LCD projector, a digital camera and a computer as shown in Figure 5.1. A LCD projector projects a mesh pattern to examinee's body and muscle boundary lines, these are drawn by an expert of surface anatomy with a bright pen. A digital camera captures this body image and sends it to a computer. On this computer, an image processing is performed and a 2-dimentional image is translated to 3D polygon information. Furthermore, the boundary lines also detected as textures and vectorized lines through this image processing.

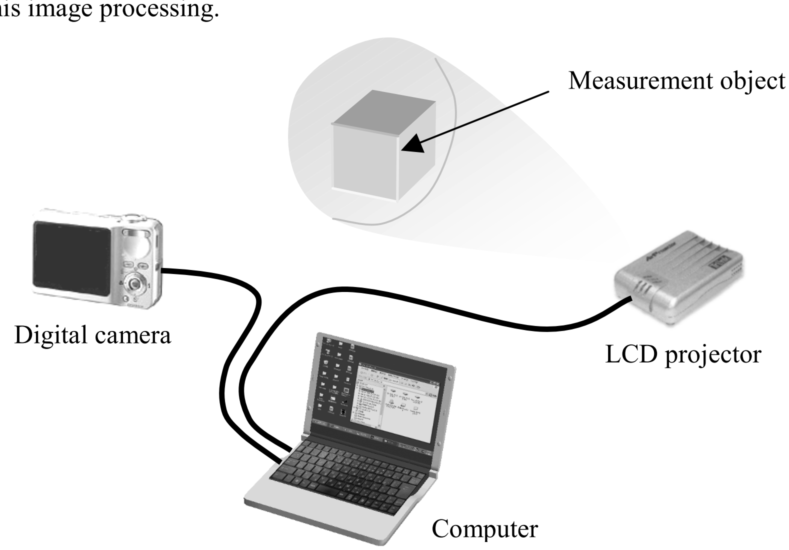


Fig.5.1 System configuration

5.2 3D measurement

If the corresponding intersection points of a mesh pattern in a captured 2D image to intersection points projected by a projector are found out, 3D position of each intersection points can be easily obtained by triangulation method.

5.3 Image processing

The captured image by a digital camera is sent to and manipulated on a computer. A projected mesh pattern in captured image is converted a vectorized mesh model at short times through the following image processing procedure.

(a) Binarization

Binarization is performed with an optimal threshold obtained by Ohtsu's method. A obtained histograms from a captured images is clearly divided into low intensity pixels and high intensity pixels, and tend to be diphasic, therefore the Ohtsu's method which can find the dale in the diphasic histogram as a threshold is suited for our purpose as shown in Figure 5.2.

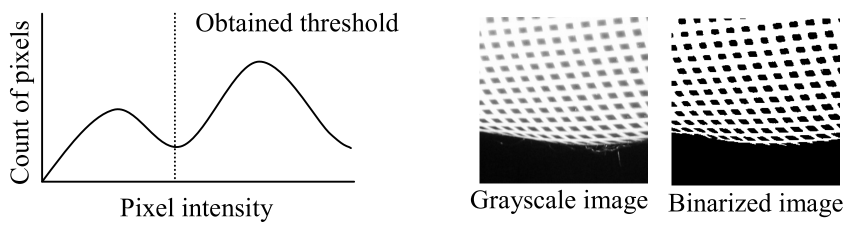


Fig.5.2 Binarization

(b) Thinning for detection of mesh pattern

As a preprocessing for finding intersection points in a captured image, a thinning technique is applied. As shown in Figure 5.3, the thick lines are translated one pixel thickness lines by grinding down recrementitious pixels.

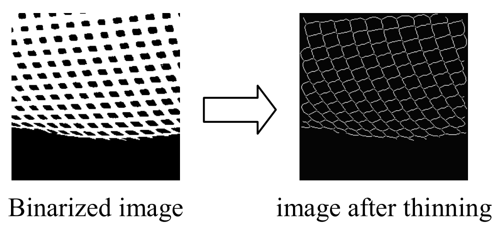


Fig.5.3 Thinning

(c) Detection of intersection points of mesh pattern

To find vertex of polygons, intersection points are detected by surveying pixels laying side by side of each pixels. Furthermore, to avoid detection of discarded intersection points, those are generated by the error in thinning process, the intersection points those placed near each ether are merged as one intersection point as shown in Figure 5.4.

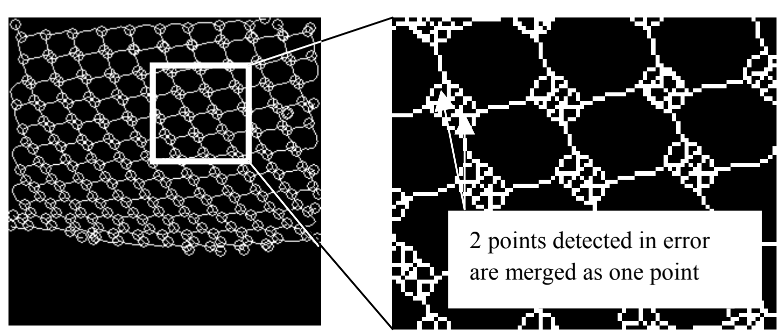


Fig.5.4 Detection of intersection points

(d) Detection of muscle boundary lines drawn by an expert of surface anatomy

The boundary lines drawn by an expert of surface anatomy is detected by binarization process, and put it on as a texture using texture-mapping technique. Furthermore, using image processing through (a) to (c) above, the muscle boundaries also stored as vectorized information.

5.4 Experiment and result

An experiment to evaluate applicability of developed 3D measurement system for our sensor suit is performed. In this experiment, we focused on the muscle boundary lines of human legs. Figure 5.5 shows examinee's leg image with the muscle boundary lines drawn by an expert of surface anatomy. Background of the examinee is covered with black drape to avoid false detection of image processing.

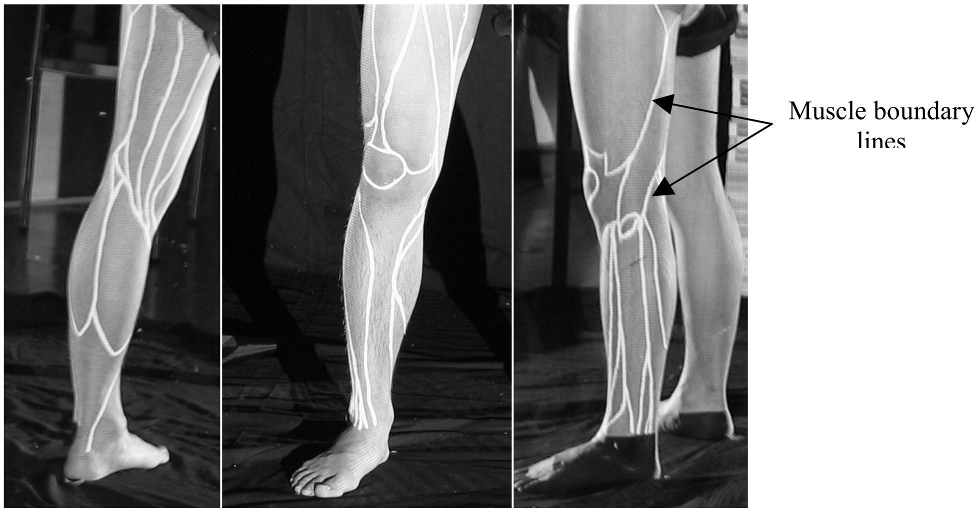


Fig.5.5 Image of leg with muscle boundary lines

Figure 5.6 shows the detected 3D polygon mesh by capturing a projected grid pattern. As shown in this figure, the shape of examinee's leg is transformed 3D polygon model correctly. Because of the short measurement time, it is possible to capture the leg image and transform it to 3D polygon mesh continuously to generate animation data as shown Figure 5.7.

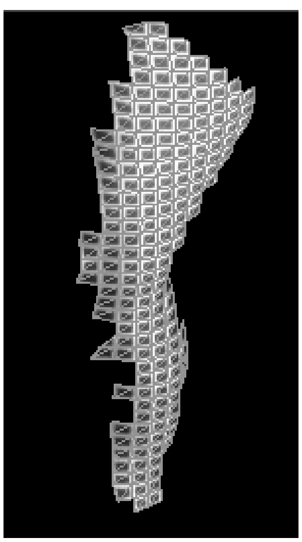


Fig.5.6 Measured 3D polygon mesh

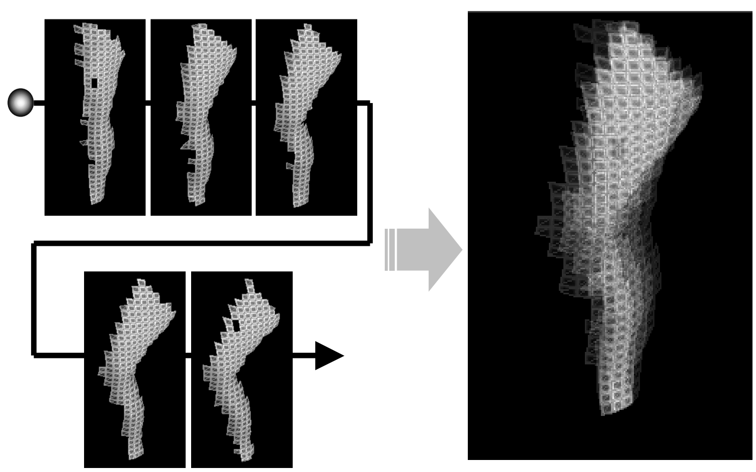
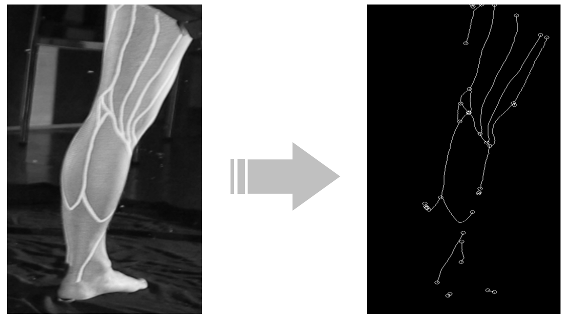


Fig.5.7 Creation of animation

Figure 5.8 shows a detected corresponding muscle boundary lines drawn by an expert of surface anatomy. As shown in this figure, the boundary lines also clearly detected and translated to vectrized information.



Photograph with Vectorized

Fig.5.8 Creation of animation

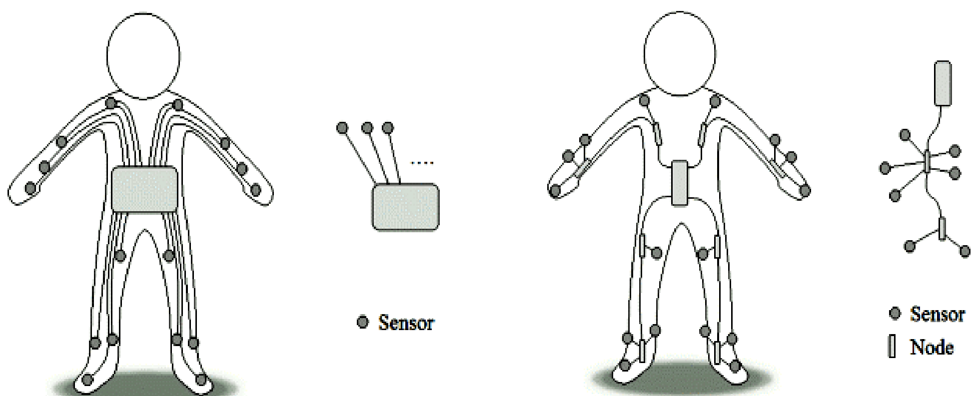
5.5 Summary

3D Measurement and imaging processing system for detection muscle position and boundary has been developed. Using developed system, a database on human motions and corresponding muscle boundary lines drawn by an expert of surface anatomy can be quickly established. Based on such a database, the optimal numbers and locations of sensors on the sensor suit can be effectively determined.

6. Sensor Network

6.1 sensor network using microcomputer

The increase of sensors causes the increase of electric wires in the suit, which decrease the robustness of the data transmission. To cope with this problem, we have developed a sensor network with minimum lengths of electric wires. As illustrated in Figure 6.1, the developed sensor network has a much simpler network configurations and thus less susceptible to damage.



Before introduction of sensor network After introduction of sensor network

Fig.6.1 Sensor Network

6.2 Prototype of sensor network

Experimental sensor networks were fabricated. Figure 6.2 shows a sample of the accelerometer network. A routing algorithm used for the Internet connection is applied for this network. Even if some parts of the network suffer from damage, the sensor network still can works properly to transmit all the sensor data to the controller. Figure 6.3 illustrates how the sensor network works after a portion of the network is damaged.

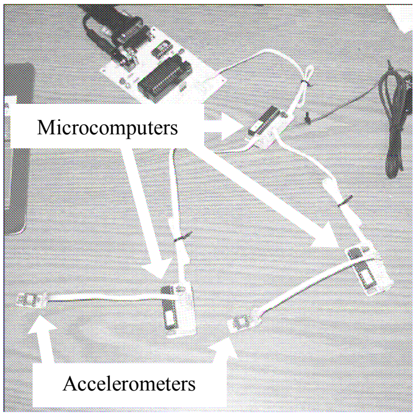


Fig.6.2 Prototyped network of accelerometer

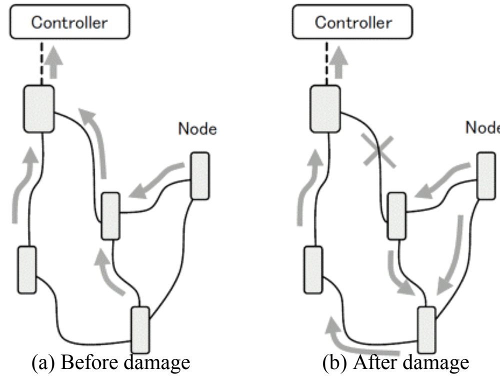


Fig.6.3 Sketch of the decentralized network connection

6.3 Simulation

This failure-tolerant feature of the sensor network is confirmed through the computer simulation. The virtual network on the computer screen is shown in Figure 6.4. Excellent sensing abilities as well as high reliability of the sensor network system are demonstrated through both experiments and computer simulations.

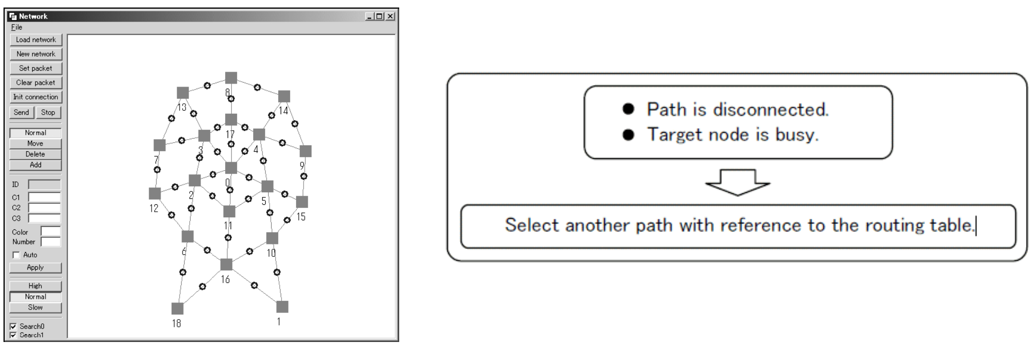


Fig.6.4 Computer simulation of the decentralized network connection

6.4 Experiment and result

To evaluate our system, we have tested our sensor network system with small sized sample network as shown Figure 6.5 and computer simulation software. Each node has a microcomputer and proper routing table stored in its computer. Each node has also LED on its main board so that we can check the packet position and movement with eyes. In this network, a packet is sent from node 3, and the destination of the packet is node 0.

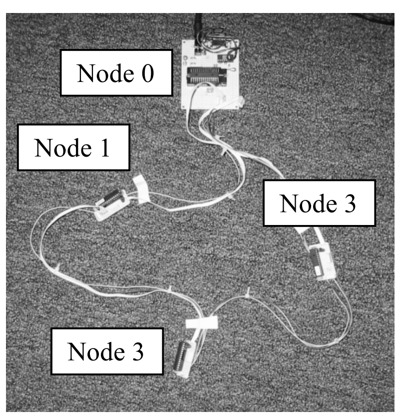


Fig.6.5 Sensor network for experiment

Figure 6.6 shows the actual movement of data packet under condition 1 and condition 2. Condition 1 is assumed that connection cables are not damaged, and conndition2 is assumed that the connection cable, which connects node 3 and node 2 is damaged. As shown in Figure 6.6, In case of condition 1, the packet sent from node 3 is transmitted through the optimal path according to the

routing table. In case of condition 2, the connection cable, which connects node 3 and node 1 is damaged. However, the packet sent form node 3 is correctly transmitted to the destination node 0 with avoiding the damaged connection.

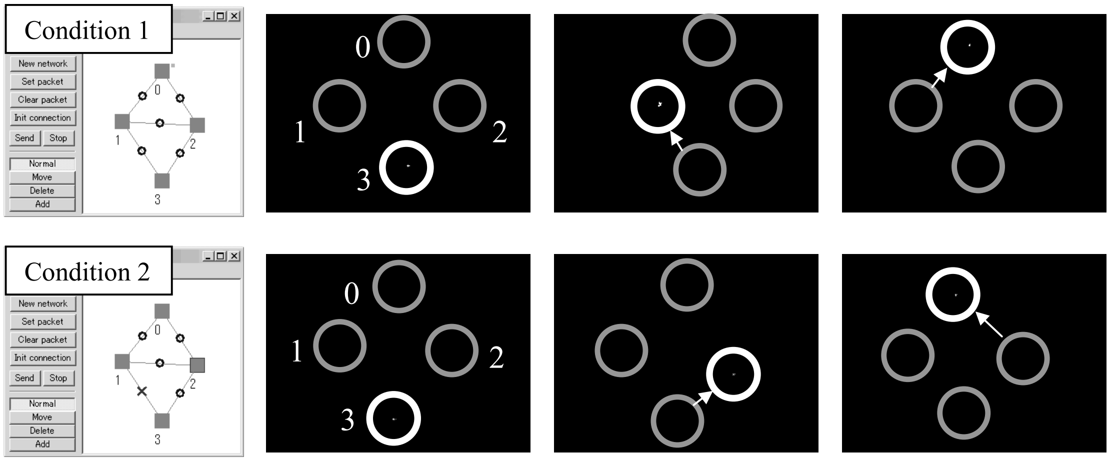


Fig.6.6 Experimental result

6.5 Summary

A sensor network system has been developed. The developed sensor network has a much simpler network configurations and thus less susceptible to damage. Furthermore, the computer simulation software also has been developed. We successfully confirmed the efficiency of our sensor network system through the experiment using actual small network and simulation software.

7. Auto-Calibration System for EMG Sensor Suit

An innovative haptic sensor suit with a distributed sensing capacity is being developed based on the fact that human motion is actuated by certain muscles, and thus the shape, stiffness and density of the muscles change accordingly with the motion and loading conditions of the human body. The proposed suits are made of soft elastic fabrics in which arrays of tiny sensor disks and optical fibers are embedded. The sensor disks are made of strain gauges and ultrasonic sensors for measuring stiffness and density of the muscles. The different types of sensor are integrated in the sensor suit and the data from all these different sensors are fused to achieve accurate and reliable measurement of the muscle conditions and motion and furthermore reliable estimate of torques of the operator. This estimated torque can be used to accurately control the power amplifier in a timely manner. In our project, an innovative haptic sensing system with a distributed sensing capacity is proposed. We introduced tile electrode, in order to cope with the problem. The experiment, which presumes torque from line potential using EMG sensor suit, was carried out to examine the validity of the system.

7.1 EMG Sensor Suit

Developed auto-calibration system is focused on EMG sensors. Because, EMG is the most effective sensor, which can perform the biometry. However, it is difficult to equip the place same each time with a sensor disk, and sensor disk will move during wearing. The elasticity in which a suit has these problems is the cause. To measure the accurate EMG, the sensors embedded in our suit should focus on the aggregate of neuromuscular junction called innervation zone. To cope with this problem, a tile-like sensor disk has been developed as shown Figure 7.1. The EMG sensors, which detects EMG is shifted according to the position of innervation zone as shown Figure 7.2.

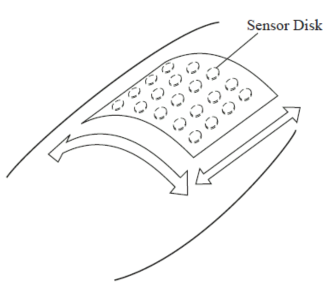


Fig.7.1 Tile-like sensor disk

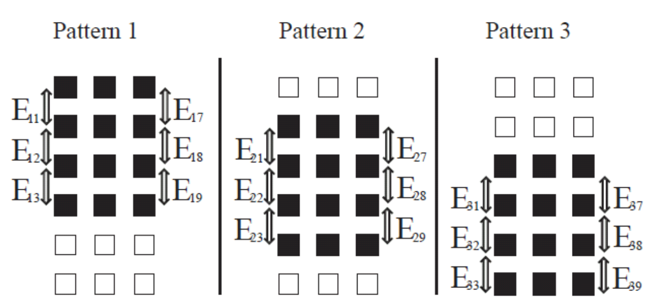


Fig.7.2 Division method of tile electrode

7.2 Detection of innervation zone

The position of innervation zone can be estimated by using correlation coefficient of each waveform obtained from EMG sensors. The line EMG waveform actually measured with the array electrode of three channels is shown in Figure 7.2. From this, it can check

that correlation is in the waveform of Ch.1 and Ch.2. Moreover, the waveform of Ch.2 and Ch.3 can check that it is also reversed. We describe how to actually presume the position of innervation zone using an array electrode. As shown in Figure 7.3, when the array electrode of three channels is used, the position of five innervation zone can be considered. The tendency of the position of the nerve rule belt and the correlation coefficient of each channel was shown in Table 1. Moreover, Co.1 was set to the correlation coefficient between Ch.1 and Ch.2. Co.2 was set to the correlation coefficient between Ch.1 and Ch.3. Co.3 was set to the correlation coefficient between Ch.2 and Ch.3.

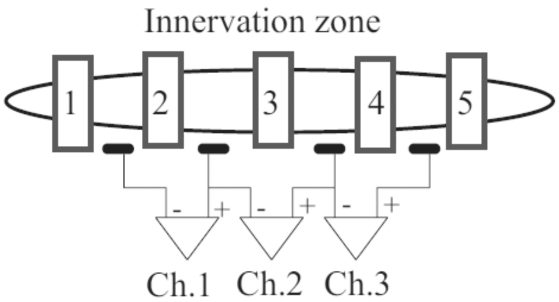


Fig.7.3 Relation between innervation zone and EMG sensors

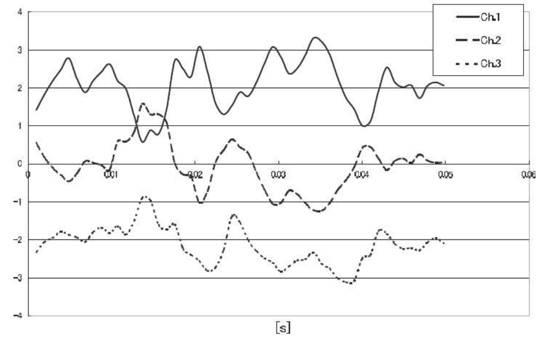


Fig.7.4 EMG signal influenced of shell innervation zone

Table 1 Relation between position of second and correlation of each channel

innervation zone	Co.1	Co.2	Co.3
1st	High	High	High
2nd	Low	Low	High
3ed	Low	Low	Low
4th	High	Low	Low
5th	High	High	High

7.3 Experiment and experimental result

An experiment of a joint torque presumption from tile EMG electrode was performed. In this experiment, knee joint torque is presumed from tile electrode attached on examinee's thigh as shown in Figure 7.5-(a). The detected EMG signal is amplified 10000 times with amplifier (amplifier NIHON KOUDEN MME-3116) and 5Hz highpath filter is applied. Simultaneously, joint torque is measured by a torque-measuring (Figure 7.5-(b)) instrument. Teaching data was measured using the tile electrode arrayed by 5 x 3. Total of six patterns including two patterns perpendicular to the direction of a muscular fiber and parallel at each joint angle (30◦, 60◦, 90◦) was measured. For verification, we measured EMG signal nine times with 3 x 3 EMG sensor array as shown in Figure 7.2.

(a) The way a tile electrode should stick

(b) Torque sensor

Figure 7.5 Measurement apparatus used in experiment

Table 2 Correlation coefficient of EMG map

(a) Parallel to a muscular fiber

	Verification data		
Teaching data	Pattern 1	Pattern 2	Pattern 3
Pattern 1	0.99	0.82	0.54
Pattern 2	0.82	0.99	0.72
Pattern 3	0.53	0.69	0.99

(b)Perpendicular to a muscular fiber

	Verification data		
Teaching data	Pattern 1	Pattern 2	Pattern 3
Pattern 1	0.99	-0.48	0.32
Pattern 2	-0.49	0.99	-0.33
Pattern 3	0.34	-0.35	0.99

As shown in Table 2, the correlation coefficients are high at the time, when the pattern of teaching data and verification data has overlapped. From this result, the effectivity of EMG tendency map for the purpose of presumption of a position error is confirmed.

7.4 Summary

An auto-calibration system for EMG sensor suit has been developed. This developed sensor suit has tile-like EMG sensors. Using this tile-like sensor array, the innvertion zone in human body, where is the proper position for EMG sensors to measure EMG signal can be detected correctly. The applicability of this auto-calibration system is confirmed through the torque estimation experiment. Now we can combine this system with our sensor suit.

8. Conclusion

An innovative sensor suit is developed, which can be conveniently put on by an operator to detect his or her motion intention by non-invasively monitoring his or her muscle conditions such as the shape, the stiffness and the density. This sensor suit is made of soft and elastic fabrics embedded with arrays of MEMS sensors such as muscle stiffness sensor, ultrasonic sensors, EMG sensors, accelerometers and optical fiver sensors, to measure different kinds of human muscle conditions. In this project period, we successfully developed the sensor suit, which can estimate operator's torque using tile-like EMG sensor array with an auto-calibration system. Moreover, the other sensors for measurement of human body condition including the muscle stiffness sensor, the muscle density sensor, the MEMS accelerometer and the fiber optic sensor have been successfully developed in this project and their accuracy and reliability demonstrated. We had also demonstrated broad potential applications of these sensors, particularly in the biomedical field. As an example, we presented a device for assisting grasping function using the muscle stiffness sensor and the sensor network developed in this project.

9. References

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b.(5)

Interactions with medical field:

1.Device for assisting grasping function using muscle stiffness sensor
2.Rehabilitation system of hand manipulation using optical fiber.
3.Communication device for serious disabled using MEMS accelerometer
4.Wearable sensor network system for walking assistance